UNITED STATES DISTRICT COURT
WESTERN DISTRICT OF NEW YORK

SAMUEL M. ROBERTS,

Plaintiff,

vs.

LOS ALAMOS NATIONAL SECURITY, LLC, AWE, PLC., MASSACHUSETTS INSTITUTE OF TECHNOLOGY,

Defendants,
Third-Party Plaintiffs,

vs.

UNIVERSITY OF ROCHESTER

Third-Party Defendant.

SECOND SUPPLEMENTAL RESPONSE TO PLAINTIFF'S DEMAND FOR DISCOVERY

Civil No. 11 CV 6206L

Defendant/Third-Party Plaintiff, Los Alamos National Security, LLC (hereinafter "Los Alamos"), by and through its attorneys, Woods Oviatt Gilman LLP, provides its Second Supplemental response to Plaintiff's First Demand for Discovery and Inspection, as follows:

PRELIMINARY STATEMENT

By responding to Plaintiff's Demand, Defendant Los Alamos does not waive any objections it may have regarding the use of information regarding the truth or accuracy of any characterizations or assumptions contained in the Demand. Defendant Los Alamos reserves its rights to make all objections identified herein or object on other grounds as to the use or admissibility of the information provided, in whole or in part, or the subject matter covered thereby, in any proceeding or trial or in any other action. Defendant Los Alamos reserves its right to object on any and all proper grounds and it, in no way, admits as to the authenticity, competency, relevance, materiality or admissibility of any of the information provided herein.

Woods Oviatt Gilman LLP
700 Crossroads Building
2 State Street
Rochester, New York 14614

The responses of Defendant Los Alamos are, and will be, based upon information acquired thus far, and Defendant Los Alamos reserves the right to amend or supplement its responses in accordance with the Federal Rules of Civil Procedure and the Local Rules of this Court. By responding to this Demand, Defendant Los Alamos does not waive any objections it may have with regard to Plaintiff's use of the information or regarding the truth or accuracy of any characterizations or assumptions contained in Plaintiff's Demand. Defendant Los Alamos reserves its right to make all objections identified herein or object on the grounds, comment as to the use or admissibility of information provided, in whole or in part, or the subject matter covered thereby, in any proceeding or trial or any other action. Defendant Los Alamos reserves its right to object on any and all proper grounds and it in no way admits the authenticity, competency, relevance, materiality or admissibility of any of the information provided herewith.

The responses of Defendant Los Alamos are, and will be, based on the information acquired thus far, and it reserves the right to supplement its responses in accordance with the Federal Rules of Civil Procedure and the local rules of this Court.

GENERAL OBJECTIONS

1. Defendant Los Alamos objects to each request, instruction or definition to the extent that any of them seek to impose any obligation beyond that required by the Federal Rules of Civil Procedure or the Local Rules of this Court.

2. Defendant Los Alamos objects to each request to the extent it could be construed to seek information which may be covered by the attorney-client privilege, the work-product privilege, or any other applicable privilege doctrine.

3. Defendant Los Alamos objects to each request to the extent that it may be construed to seek information which is proprietary and/or confidential or otherwise restricted from disclosure to the general public.

4. Defendant Los Alamos objects to each demand that does not specify a time frame on the ground that such demands are overbroad and not reasonably calculated to lead to the discovery of admissible evidence.

5. Defendant Los Alamos objects to each demand to the extent that it purports to require the discovery of information not within its possession, custody, or control.

6. Defendant Los Alamos objects to any interpretation of each demand to the extent that it calls for information that does not refer to or relate to matters alleged in the above-captioned action.

7. Defendant Los Alamos objects each demand to the extent the Notice to Produce seeks information that is neither relevant nor reasonably calculated to lead to the discovery of admissible evidence.

9. Unless otherwise specified, all general objections apply to each numbered answer as if each general objection was specifically set forth therein.

SECOND SUPPLEMENTAL RESPONSES TO SPECIFIC DEMANDS

1. See materials attached as ***Exhibit A***.

2. See materials attached as ***Exhibit A***.

The Defendant/Third-Party Plaintiff Los Alamos National Security, LLC reserves the right to amend and/or supplement its responses to these requests as may be appropriate.

Woods Oviatt Gilman LLP
700 Crossroads Building
2 State Street
Rochester, New York 14614

Dated: October 5, 2012
Rochester, New York

WOODS OVIATT GILMAN LLP

By: [signature]

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CERTIFICATE OF SERVICE

I, GRETA K. KOLCON, ESQ., attorney of record for Defendant and Third-Party Plaintiff, Los Alamos National Security, LLC, in the above-styled and referenced matter, do hereby certify that on October 5, 2012, the annexed Second Supplemental Response to Plaintiff's Demand for Discovery was served via United States Postal Service and e-mail on the following attorneys of record:

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THIS, the 5th day of October, 2012.

WOODS OVIATT GILMAN LLP

By: ______________________________

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<u>Exhibit "A"</u>

Go To RID#

This RID#: 25865
Last Modified: 08-Aug-2008 11:49:53

Facility Status
Comments/Problems

OMEGA Shot Request Form

UR LLE

XOPS Beamlines

General > Drivers > Target > Beams > TIM > Fixed > Neutronics

Help

Neutron Diagnostic Configuration (Help)

Select Primary Radiation: DT

Enter expected (not estimated) yield 5.00e+12

Defaults - **Neutron detectors recommended for the above parameters**

- Selections may be edited.
- Press Update to save the final configuration.

Diagnostic Description	Priority	
Activation Retractor Copper (ACTR)	Primary	Set up
CVD Neutron Bang-Time Detector 1 (CVDNBT)		
H10 CVD at 5.0m 5.0MCVD (H10CVD)		
H10 Photo Diode at 5.3m PDD99 (PDC)		
H10 Photo Diode at 5.3m PDO40 (PDC)		
H15 Re-entrant Tube CVD 1-6 (H15DCVD)		Set up
High Yield Neutron Bang-Time Detector 1 (HYNBT)	Secondary	
LANL LDRD Beta Mix P4G (BMIX)		Set up
LANL LDRD Beta Mix SCNT (BMIX)		Set up
LANL LDRD Beta Mix SiTel (BMIX)		Set up
NIF nTOF detector 1 (NIF-NTOF)		Set up
Neutron Bang-Time Detectors LLE (BTDET)		
Neutron Temporal Diagnostic 1 (NTD)	Primary	Set up
P11-NBT4.5m 1 (P11_NBT45)		Set up
Particle Temporal Diagnostic N (PTD)		**Select PTD on TIM 5**
Scintillator Counter A 3M LARD (SCC)		
Scintillator Counter B 2x2 (SCC)		
Scintillator Counter C 3M NTOF (SCC)		
Scintillator Counter D 5.4M NTOF (SCC)		

Scintillator Counter E 1.7M NTOF (SCC)	
Scintillator Counter F 12M NTOF L (SCC)	Primary
Scintillator Counter G 12M NTOF H (SCC)	Primary

nTOF LaCave Diagnostics

Set up

Setup sheets are not required for the NIS diagnostics.

Comments:

Reminder: Use the NTD Set up page to define the NTD configuration.

Campaign Editor | Drivers Editor | Beam Editor | SRF Auditor

Update | Copy ... | Reports | Station Reports

To: Vladimir Glebov <vgle@lle.rochester.edu>
From: "Hans W. Herrmann" <herrmann@lanl.gov>
Subject: DTRat
Cc: Colin Horsfield
Bcc:
Attached:

Vladimir,

We were planning to put PTD in TIM-5 on Aug 6, but MIT does not want to use it in DT. So TIM-5 is now available for your use. I tentatively placed CVD Diamond Detector - 1 in TIM-5. You have PI access to the SRF's if you would like to change this. So far, they are RID's 25865 (DT/3He) and 26170 (D2/3He)

We would like to run the light pipe with CO2 and a fast PMT/SCD scope like we did last year. I expect Colin to be interacting with you on this again.

thanks,
Hans

Hans W. Herrmann, Ph.D., CDR (Ret., USNR)
P-24 Plasma Physics, M/S E526
Los Alamos National Laboratory
Los Alamos, NM 87545
herrmann@lanl.gov
505-665-5075
fax: 667-0405

if Foreign correspondence: TSPA or Correspondence

[X] Unrestricted (P-DIV-POL-020, Att. 1, Rev. 0, 28 March 2006)
[ ] - Non-Technical Correspondence
[X] - Technical Correspondence
LA-UR [ ] - LA-CP [ ] - LALP [ ]
Reviewed [ ] ADC -
DUSA ADTO [ ]
DUSA HEP [ ]

To: vladimir Glebov <vgle@lle.rochester.edu>, wilke@lanl.gov
Subject: SRF Setups
X-Attachments: C:\Documents and Settings\121744.WIN\My Documents\GCD\GCD Data\GCD_Aug08\DTRat'08 Shot List.xls;

Vladimir & Mark,

I've attached the Shot List for DTRat'08 coming up on Aug 6. DD-RIC & NIS are listed as Ride Alongs on the SRFs. I would appreciate it if you could up date the setup sheets for these diagnostics by COB on Monday.

Vladimir- I've also tentatively included HYNTD as a primary diagnostic for the DT/3He shots (CO2 mode) and secondary for D2/3He shots (Scintillator). We can discuss next week.

thanks,
Hans

Hans W. Herrmann, Ph.D., CDR (Ret., USNR)
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Reviewed [ ] ADC -
DUSA ADTO [ ]
DUSA HEP [ ]

To: Vladimir Glebov <vgle@lle.rochester.edu>
From: "Hans W. Herrmann" <herrmann@lanl.gov>
Subject: [Fwd: BetaMix - 9/18/08]
Cc: Paul Keiter <pkeiter@lanl.gov>
Bcc:
Attached:

Vladimir,

Now that BetaMix has been moved to September, what is planned for Aug 7? Will it still be high yield? If so, do you know if it might be possible to swap this day with the DTRat shot day planned for Aug 6. I had been talking to Gary about this possibility so that GCD could have a day to ride-along before a dedicated shot day.

thanks,
Hans

-------- Original Message --------
Subject: BetaMix - 9/18/08
Date: Mon, 07 Jul 2008 14:38:06 -0400
From: John Soures <jsou@lle.rochester.edu>
To: gpgrim@lanl.gov
CC: slou@lle.rochester.edu, ssta@lle.rochester.edu, smor@lle.rochester.edu, pien@lle.rochester.edu, csan@lle.rochester.edu, ddm@lle.rochester.edu, dmay@lle.rochester.edu, pmck@lle.rochester.edu, thorp@lle.rochester.edu, jkel@lle.rochester.edu, mbon@lle.rochester.edu, dhar@lle.rochester.edu, jlab@lle.rochester.edu, jste@lle.rochester.edu, jsou@lle.rochester.edu, pkeiter@lanl.gov

The OMEGA Scheduling Committee approved the rescheduling of your previously scheduled BetaMix experiment. The experiment is now scheduled to be conducted on OMEGA on 18 September, 2008.

John M. Soures
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Laboratory for Laser Energetics
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(585)-275-5960 (FAX)
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Gary P. Grim

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Reviewed [ ] ADC -
DUSA ADTO [ ]
DUSA HEP [ ]

John A. Oertel
September 5, 2008
Los Alamos National Laboratory
Oertel's eye-witness account of LLE accident August 6, 2008

I was in the Omega/LLE control room at the ESO desk at ~6:30 PM retrieving trigger timing numbers for the NIS diagnostic with two ESO technicians when we heard a loud bang noise, followed by the hissing noise of venting gas coming from the target bay. The two technicians were listening on communication headsets to the loud noise and yelling of confusion from the target technicians trying to figure out what had happened. The primary concern at that point was the apparent loss of target chamber vacuum as seen from the vacuum gauge reading on the ESO control panel. Approximately 15 seconds after we heard the loud bang, one of the target technicians came running out of the target bay into the control room and instructed the shot director to call 911 and proclaimed, "we have a man down in the target bay". The shot director immediately called 911 and began relaying patient information to the 911 operators. At that point it wasn't exactly clear how badly the victim was injured and whether he was unconscious or not. The target technician actually demonstrated the position the victim was in by laying in the recovery position on the floor.

I then walked into the user room and mentioned to David Clark of P-23 (knowing that David, like myself was trained as a 1st responder) that we may want to be on stand-by for help to the victim. My assumption at this point that the victim most likely had a head wound, known to bleed a lot, and that though there was probably a bloody face with a lot of blood around there was no immediate danger of loss of life.

David and I went to the shot director and informed him and the target technician that we were 1st responders and that we were available to help. The target technician (obviously shaken by the scene) said "good, let's go". I don't remember the shot director saying anything, but he did allow us to proceed. The target technician informed David and I that others were administering CPR and we headed for the target bay. At that point the target technician said that we had to suit up in clean room clothes before we could enter into the target area. I protested repeatedly but complied to get access as soon as possible. This also reinforced my original surmising of the situation as a bloody scene, but not life threatening. I asked the target technician for a CPR barrier mask and gloves, to protect us from potential disease transmission. The technician brought us an old first aid kit that had just a few bandages and no personal protective equipment (PPE). David and I looked at each other and agreed that we would just do rescue breathing without PPE.

After continuing to protest the delay due to the requirements of having to suit up into clean room garb, we were finally allowed access into the target bay with just

coveralls, hood, facemasks and gloves, but no booties or laser safety glasses. We were told that there were no longer any eye hazards and to proceed.

Having been in the target bay many times, I led, with David and the target technician following closely behind me. When we arrived on scene, we found Sam Roberts unconscious lying in the East side of the target bay on the ground level facing up. Scott Evans (a LANL technician) and Zaheer Ali (a NSTec Operations Scientist) were administering CPR with Scott sitting by Sam's head and with Zaheer giving chest compressions. There was a considerable amount of blood surrounding Sam and there was a large angled gash across his face indicating blunt trauma. As we came into the room and to insure scène safety, I asked the group of 4 LLE target technicians that were grouped several feet to the West of the accident if there was anything else that could fall on responders. We were told the scene was safe. As David and I moved in to do a patient size up, Scott and Zaheer moved back. David checked for a pulse and proclaimed that "yes, he has a pulse". Our next concern was a clear airway, due to the significant facial blunt trauma and we were preparing to do a mouth sweep when the Rochester, NY fire department came through the door.

At that point we moved back from Sam Roberts and provided patient and situational safety information to the fire department EMT's. I stayed in the target bay for an additional ~10 minutes after Sam was moved out of the target bay. I got some absorbent towels from the target technicians to clean up the blood so that the remaining fire department responders could work safely.

In reflection, it is very unfortunate that Sam Roberts was injured, but I am very proud that the initial caregivers at Sam Roberts' side were DOE (LANL & NSTec) employees that trusted their many years of CPR training and were not afraid to do the right thing.

Lessons learned for me personally:

1. Carry my own first aid kit with me on travel.
2. Be aware of off site AED and first aid kit locations.
3. In the event of an emergency, listen objectively to the people around me, but trust my own instincts.

Hans W. Herrmann, Principal Investigator, CDR (Ret., USNR)
September 8, 2008
Los Alamos National Laboratory
Principal Investigator's account of LLE accident on August 6, 2008

On August 6, 2008, I was the Principal Investigator for the DT Ratio experimental campaign on the OMEGA laser facility. At approximately 6:30 pm, an accident occurred inside the target bay which seriously injured an LLE employee. At the time of the incident, Scott Evans (LANL) and Zaheer Ali (NSTec, LO) were performing modifications to LANL's Gas Cherenkov Detector on the upper deck of the target bay while being observed by an LLE technician escort. When they heard what sounded like an explosion, it is my understanding that the three of them went to investigate and found Sam Roberts lying in a pool of blood on the bottom deck with the LLNL/LLE "Light Pipe" diagnostic lying in a "twisted heap" near by. Apparently Sam had been struck in the face by the heavy apparatus, sustaining a deep facial laceration. The LLE escort exited the target bay to get help while Scott and Zaheer stayed with the victim to administer first aid. When they were unable to detect a pulse, Zaheer performed chest compressions while Scott maintained a clear airway and attempted to control the bleeding. Zaheer said afterward that he had administered over 200 compressions when he lost count. Scott and Zaheer maintained control of the scene for approximately 5 to 10 minutes until two additional LANL employees, John Oertel and David Clark, both trained first responders, arrived and took over administering first aid. They assessed the situation and determined that Sam did have a pulse at this point. John and David maintained control the scene for several more minutes until the Rochester emergency responders arrived on site.

Hans W. Herrmann

September's experiment, a number of imaging improvements have been initiated and thus we have high confidence for the physics experiments planned in February 2009.

[redacted] [redacted]

Figure 1: Overview of the AGEX-EOS-09 target (left) and the preliminary data from shot 52215 (right).

DTrat

In August 2008, LANL continued the *DT Ratio- ^{3}He Addition* campaign, imploding glass capsules filled with DT/^{3}He using a 600 ps square laser pulse. Previous studies have looked at the effect of adding ^{3}He to the D_2-filled capsules (as a DT surrogate)- this study is the first to look at the effect on DT. The use of DT also allows the acquisition of high quality reaction histories derived from the Gas Cherenkov Detector (GCD-1). From these reaction histories, it has been determined that the addition of ^{3}He degrades the compression component of yield more than expected. This is consistent with the conclusions of the study conducted by MIT using D_2/^{3}He-filled plastic capsules (R. Rygg, et al., Phys Plasmas 13, 052702 (2006)) and LANL's Hi-Z campaign utilizing glass capsules, also filled with D_2/^{3}He (D.C. Wilson, Jrnl Phys: Conf

Ser 112 022015 (2008)). However, contrary to the MIT study, the shock component does not appear to be significantly affected.

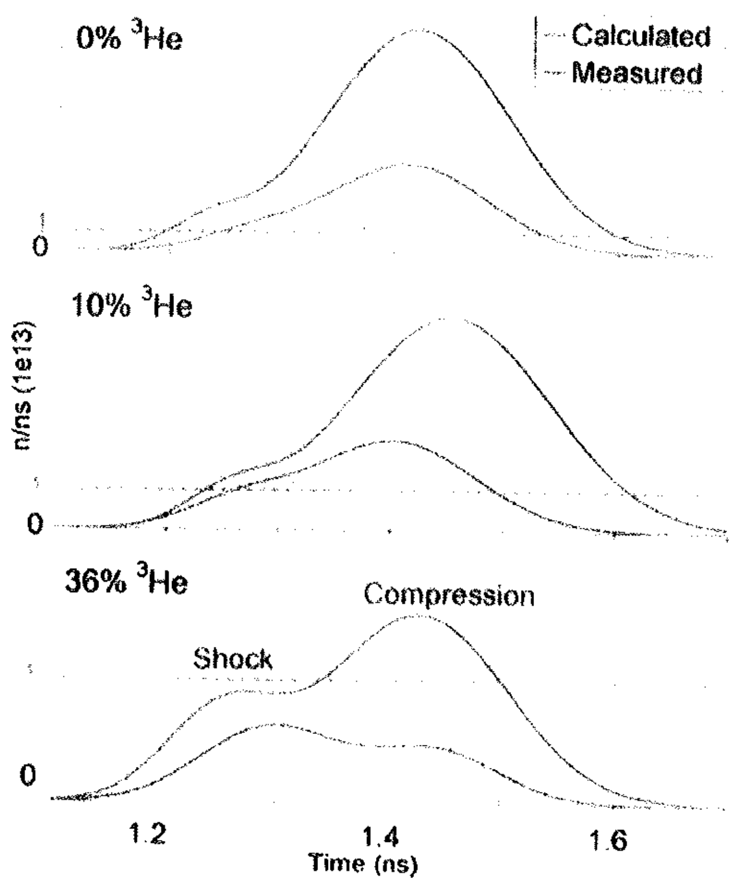

Figure 2: Calculated (convolved with residual instrument response) and measured (deconvolved GCD data) reaction histories for various ^{3}He concentrations.

Figure 2 shows the reaction histories for three concentrations of ^{3}He addition. Overall, the measured neutron yield is ~37% of a clean calculation for *each* ^{3}He concentration. However, when the histories are decomposed into Gaussian components representative of shock and

compression yields, the measured compression component goes from being a factor of three lower than calculated at 0% ^{3}He, to being a factor of five lower at 36% ^{3}He. This agrees well with the MIT study as seen in Figure 3 (the factor of 3 at 0% ^{3}He is normalized out for the DTRat data set, whereas a factor of ~2.2 is normalized out for the "Rygg" data set). In contrast, the decomposed shock component from DTRat agrees quite well with the clean calculation for all three ^{3}He concentrations as shown in Figure 4.

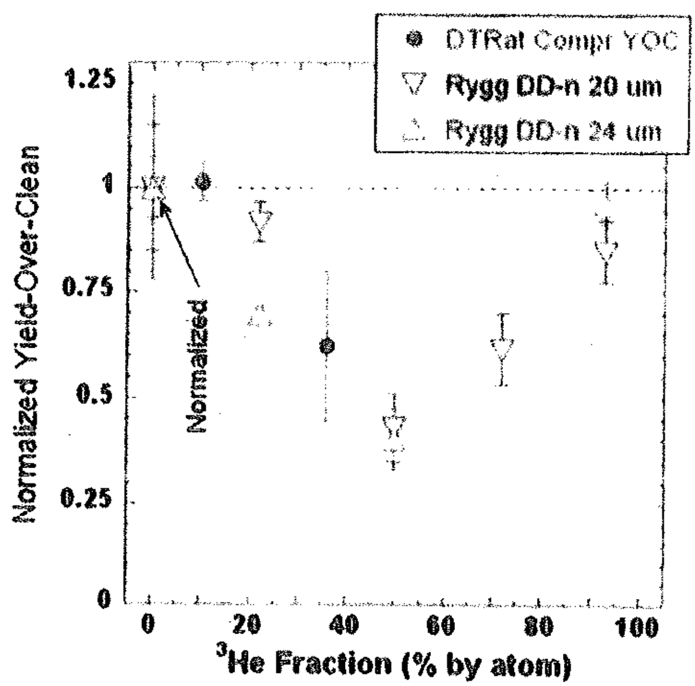

Figure 3: Scaled compression component of neutron yield normalized to one at 0% ^{3}He.

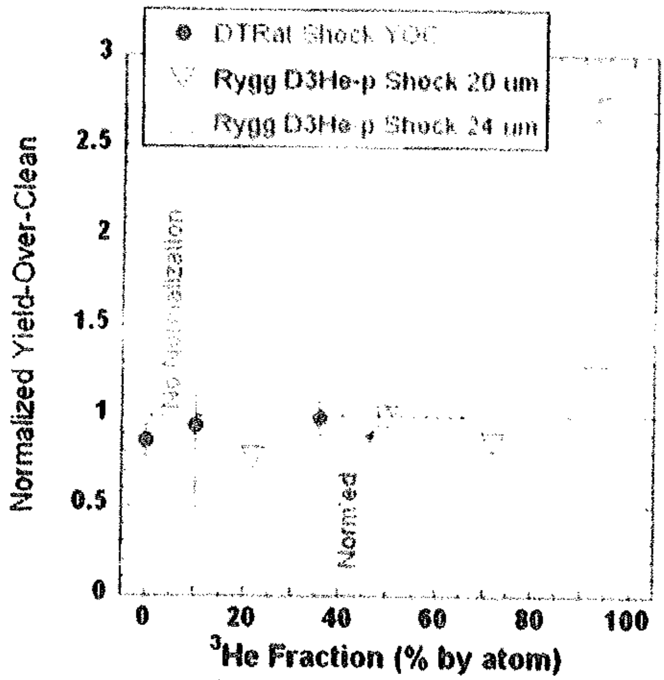

Figure 4: Scaled shock component of neutron yield normalized to one at 50% ^{3}He for "Rygg" data; no normalization for DTRat data.

Shock yield data for the 24 μm wall-thickness capsules from MIT's "Rygg" study exhibit a parabolic dependence on ^{3}He fraction, with the minimum occurring near 50% ^{3}He, similar to what was observed for the compression component. The data set for 20 μm thick walls, however, does not appear to support this trend. We suspect the degraded yield anomaly arises only after the shock has reflected from the center and has hit the incoming shell. After such time, the shock yield is diminishing while the compression yield is rising. X-ray imaging and ρR data from DTRat, Hi-Z and the MIT study support the hypothesis that capsules with ~50% ^{3}He aren't as

compressed at the time of peak neutron production rate during the compression phase as those without ^{3}He (or those with nearly pure ^{3}He from the MIT study). It is not understood at this time what is degrading the compression.

High-Z

The High Z project successfully completed its planned experiments for FY08 at the Omega laser facility. These experiments investigated the effect on fusion yield of adding He to ICF implosions. The experiment used the standard glass shell targets we have used in the past and varied the concentration of ^{3}He in the target and measure the resulting yield. These were done for 3 different concentrations of ^{3}He, 0%, 10%, and 50% by atomic fraction. The gas fills were also designed to be hydrodynamically equivalent in order to try to insure similar hydrodynamic behavior. In addition, we also planned to measure the change in yield for two different laser pulse lengths. We first used our standard pulse length of 1.0 ns and then did a second series of experiments using a shorter pulse length of 0.6 ns. The shorter pulse length should emphasize the differences in the compression component of the yield where we believe the ^{3}He is causing a significant impact.

On April 23, we successfully fired 8 shots at Omega with 1 ns laser pulses and varied the concentration of He in the capsules. The neutron yield results from these experiments are shown in Figure 5, along with the expected degradation due to having less deuterium in the target. One can see in the figure that the observed yield does fall below the expected yield as the He is increased. We also see little difference in the ion temperature for these shots, which varies from 6.9 keV to 7.4 keV and increases only slightly as the He concentration is increased.

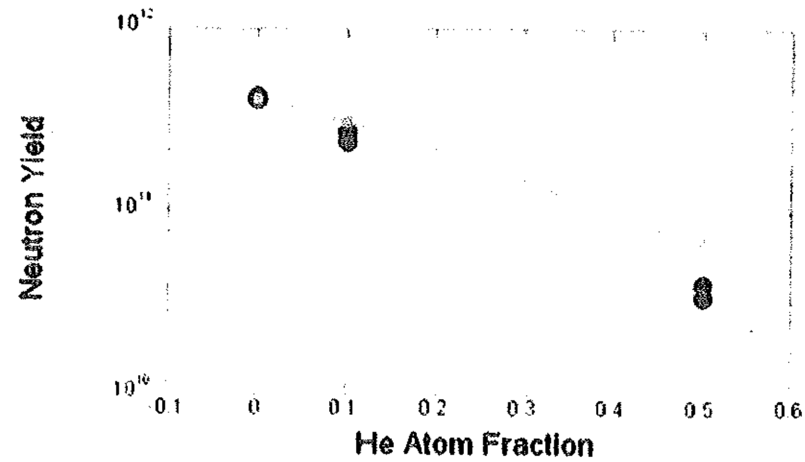

Figure 5: Neutron yield as a function of He atom fraction in the gas. The green circles are data for 1 ns pulse drive with 4.3 micron thick walls and the orange curve represents the expected yield based on the deuterium concentration only.

We also did two other shots this day with glass shells that had a thickness of 4.0 microns. These targets contained 50% atom fraction of He, but one was ^{4}He instead of the usual ^{3}He. The yields for these two shots were 4.8e10 and 4.3e10 respectively, a difference of 10%, which is similar to our standard shot to shot variation. The ion temperature for these shots was higher, ~ 8.2 keV, consistent with thinner glass and a more rapid implosion.

The remaining shots had to be done on a separate half-day June 17. We were able to get 4 shots and the results from those shots are shown in Figure 6. The behavior is similar to what we observed for the 1 ns drive shots with one exception. The ion temperatures for these experiments varied greatly, from 5.3 keV for no He to 7.8 keV for 50% He and bring into question whether the implosions are hydrodynamically equivalent. This would be consistent with an even greater

degradation of the compression burn, reducing its importance compared to the shock burn and effectively elevating the average burn temperature.

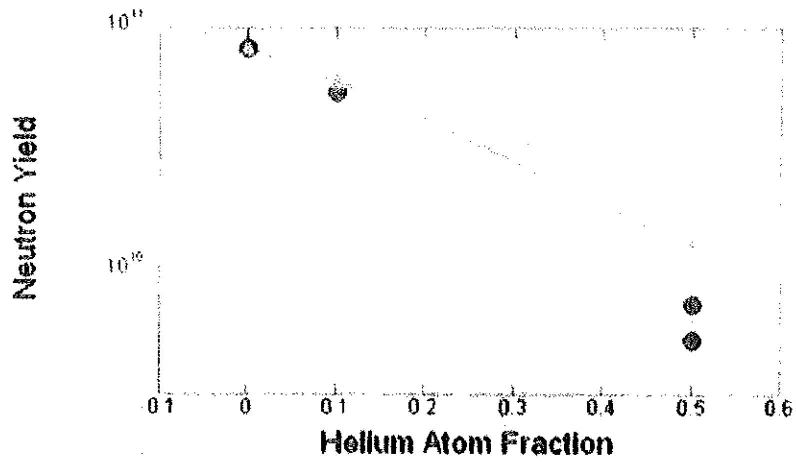

Figure 6: Neutron yield as a function of helium atom fraction in the gas. These experiments used 0.6 ns laser drive and the data is shown as the green dots. The orange curve represents the expected yield based on the deuterium concentration.

Overall, the results for doping the gas with ^{3}He were consistent with earlier results for Ar, Kr, and Xe, though a much larger atom fraction of ^{3}He was required to produce a similar effect.

NIF Platform #5

The NIF Platform #5 campaign continued experiments to develop diagnostic techniques for future NIF experiments. The FY08 experiments focused on backlighter source

characterization and development as well as the successful execution of a new platform for the observation of absorption features due to heated materials.

One aspect of the backlighters that was examined was the conversion efficiency for L-shell and M-shell emitters. Over the course of the FY08 campaign, the laser irradiance studied varied from 10^{14} W/cm^2 up to nearly 10^{15} W/cm^2. The data obtained will assist in evaluating the expected photon fluxes at the NIF. An example of some of the data obtained from a CsI backlighter is shown in Figure 7.

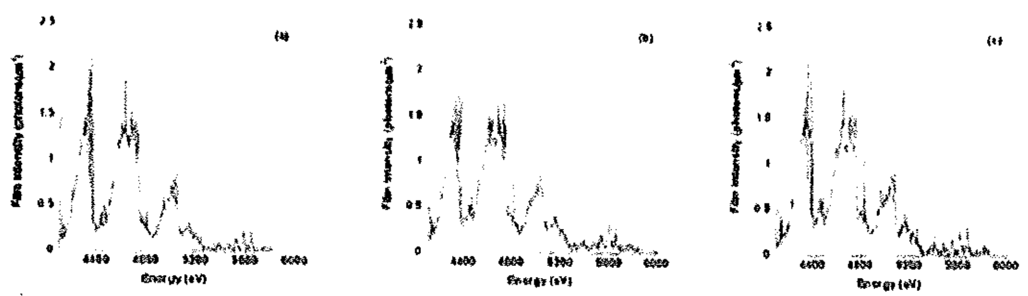

Figure 7: a) CsI spectra for a nominal 600, b) nominal 400 c) and a nominal 200(right) micron diameter spot. Note that although the laser irradiance spans an order of magnitude, the amount of emission stays essentially constant.

The platform for studying absorption spectroscopy is shown in Figure 8. A Ti foil was heated inside of a hohlraum. A CsI backlighter provided a quasi-continuum spectrum source, which passed through the sample and was recorded on by a spectrometer (Figure 9). The recorded spectrum contains both the emission from the CsI backlighter and the absorption from the heated Ti foil. Although detailed analysis is still underway, these experiments provided valuable information on the absorption spectroscopy technique and have led to a number of improvements being implemented for the future NIF experiments.

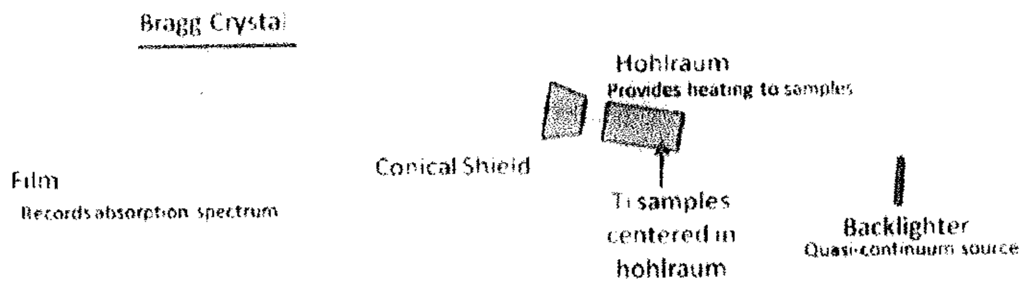

Figure 8: Picture depicting the absorption spectroscopy configuration. Laser beams enter both sides of the hohlraum. A thin Ti foil sitting in the center of the hohlraum is the heated. The backlighter provides a quasi-continuum backlighter source and its x-rays pass through the Ti sample and are reflected off the Bragg crystal and recorded on film. Some of the backlighter emission is absorbed, depending on the temperature and density of the Ti. The picture is not to scale.

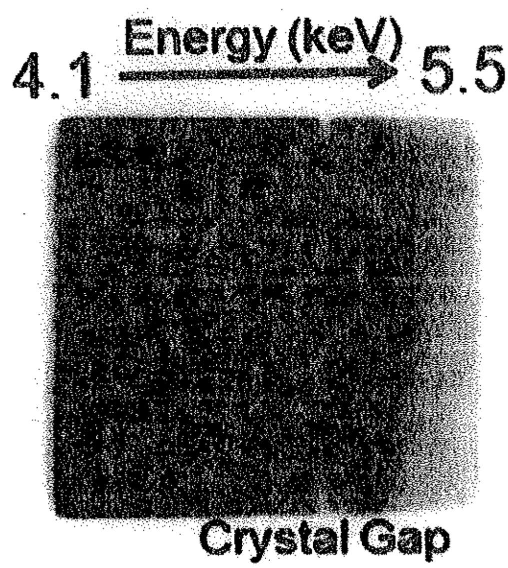

Figure 9: Spectrum containing the emission from a CsI backlighter and the absorption due to a thin, heated Ti foil.

Symergy

We have used two cones of the OMEGA laser to irradiate a linear 0.7 NIF-scale hohlraum to implode Be and CH capsules to measure the effect of beam phasing on the implosion symmetry. The vacuum hohlraums, with 2mm diameter capsules, reached 105 eV using 1 ns laser pulses. The symmetry of the x-ray emission from the implosion was measured for both the CH and Be capsules. We were able to vary the symmetry at implosion time by varying the cone fraction or ratio of energy between the inner cones [21 degrees or 42 degrees] and the outer cone [59 degree beams]. We found that the fraction where the best symmetry occurred was closest to those ratios that the re-emit technique had found for the same pointing. When we replaced the 42 degree beams by the 21 degree beams and pointed to the same location in the hohlraum with the same laser irradiance, the hohlraum radiation was lower, and the symmetry was affected, indicating some impaired propagation of the inner cone.

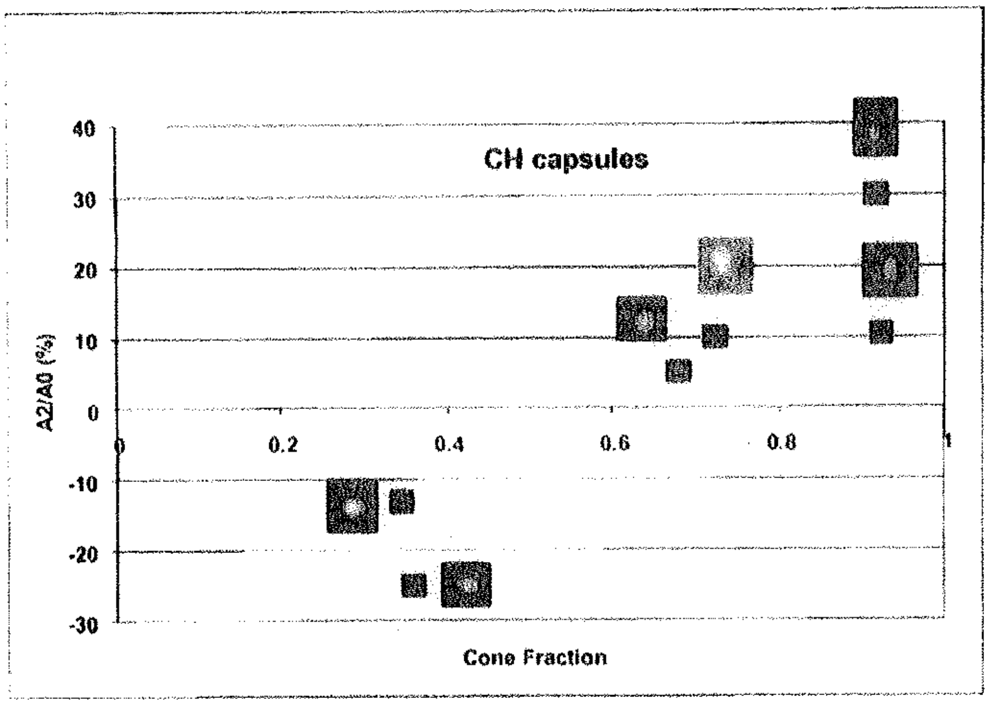

Figure 10: The measured second order Legendre coefficient for the x-ray emission at the 30% level, measured at peak emission

Aug. 27, 2008

University of Rochester Laboratory for Laser Energetics to Resume Operations

After a rigorous, three-week safety review, the Laboratory for Laser Energetics will return to operations this week.

Laboratory Director Robert McCrory initiated a voluntary "safety stand down" on Aug. 7 after an employee of the laboratory was seriously injured when a mounting bracket for a piece of diagnostic equipment broke loose while he was standing beneath it.

During the stand down, the lab's approximately 300 employees spent more than 35,000 staff hours inspecting equipment and reviewing safety procedures throughout the laboratory.

"We have carefully reviewed the safety of our equipment and procedures throughout the laboratory," McCrory said. "We have every confidence moving forward that we have eliminated to the degree possible the risk of a similar accident occurring again."

McCrory said that the recommendation to University of Rochester President Joel Seligman to resume operations was made after the equipment in question was removed from service and it was determined through the safety reviews that no other equipment in use at the laboratory poses a risk of a failure of this type. The recommendation was supported by Jeffrey Williams, a former Acting Associate Director for Engineering at Lawrence Livermore National Laboratory and an expert in laboratory accident analysis who independently reviewed the safety stand down procedures and analysis. The University's Office of Environmental Health & Safety also separately audited the review and inspections and fully supports the laboratory's return to operations.

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Anomalous yield reduction in direct-drive deuterium/tritium implosions due to ^{3}He addition[a)]

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Glass capsules were imploded in direct drive on the OMEGA laser [Boehly *et al.*, Opt. Commun. **133**, 495 (1997)] to look for anomalous degradation in deuterium/tritium (DT) yield and changes in reaction history with ^{3}He addition. Such anomalies have previously been reported for D/^{3}He plasmas but had not yet been investigated for DT/^{3}He. Anomalies such as these provide fertile ground for furthering our physics understanding of inertial confinement fusion implosions and capsule performance. Anomalous degradation in the compression component of yield was observed, consistent with the "factor of 2" degradation previously reported by Massachusetts Institute of Technology (MIT) at a 50% ^{3}He atom fraction in D_2 using plastic capsules [Rygg, Phys. Plasmas **13**, 052702 (2006)]. However, clean calculations (i.e., no fuel-shell mixing) predict the shock component of yield quite well, contrary to the result reported by MIT but consistent with Los Alamos National Laboratory results in D_2/^{3}He [Wilson *et al.*, J. Phys.: Conf. Ser. **112**, 022015 (2008)]. X-ray imaging suggests less-than-predicted compression of capsules containing ^{3}He. Leading candidate explanations are poorly understood equation of state for gas mixtures and unanticipated particle pressure variation with increasing ^{3}He addition. *© 2009 American Institute of Physics.* [DOI: 10.1063/1.3141062]

I. INTRODUCTION

Inertial confinement fusion (ICF) implosions have been conducted at US laser facilities such as NOVA and OMEGA and soon at the nearly completed National Ignition Facility (NIF). OMEGA experiments are based predominantly on direct drive, in which laser beams impinge directly on the ICF capsule.[1] NOVA was, as NIF will be, based predominantly on indirect drive in which the laser beams impinge upon the inside of a *Hohlraum*, generating a uniform bath of x rays which indirectly illuminate the capsule. In both cases, ablation of outer capsule material results in a rocket effect which compresses the remaining capsule material inward, heating and compressing the fuel primarily through pressure times change in volume (pdV) work. Additional heating comes from the initial shock received from the laser onset.

As a result, fusion product yield can be separated into two components—shock and compression yields. If the velocity of the laser-driven shock is greater than the maximum velocity of the shell, the shock can break out of the shell, travel inward through the fusion fuel, rebound at the center of the capsule, and travel outward through the fuel again. As it does so, the fuel ionizes and heats to high ion temperatures (e.g., ~10 keV), producing fusion yield before the capsule has reached maximum compression. The fuel can then cool back down after shock heating as the capsule continues to compress to maximum density, producing additional fusion yield at higher ion density but at lower ion temperature (e.g., ~5 keV). Ideally, shock and compression yields coincide, providing a synergy that maximizes fusion yield. However, experiments in which the final shell velocity is reduced, by using thick-walled capsules or by shortening of the laser pulse duration, enables one to study the individual yield components. Such studies allow additional insights into the dynamics of capsule implosions. Discerning these components of yield necessitates the ability to measure deuterium/tritium (DT) reaction histories with high precision. This study used the gas Cherenkov detector (GCD),[2–4] developed at Los Alamos National Laboratory, which relies on the DT fusion gamma-ray output for high-bandwidth measurements (~4 GHz). Gaussian decomposition of the reaction history allows one to approximate the separate bang times (i.e., time of peak of fusion reactivity) and total yields for each yield component.

While relatively efficient in terms of laser energy coupling, direct drive can also result in a higher level of spatial nonuniformities, giving rise to hydrodynamic instabilities, such as the Rayleigh–Taylor instability. These instabilities are known to result in fuel/shell mix which acts to cool the fuel and degrade the fusion yield. Radiation hydrodynamics codes [one dimensional (1D) and two dimensional] are rou-

[a)]Paper BI 1 3, Bull. Am. Phys. Soc. **53**, 19 (2008).
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tinely used to calculate the performance of these implosions. These codes, however, typically overpredict the neutron yield, generally by factors of 2–4. Fuel-shell mix is often invoked in order to degrade the "clean" yield calculation and match the experimentally measured values.

In the current study, ^{3}He was added to capsules containing deuterium and tritium fuels. The ^{3}He was observed to degrade the fusion yield more than predicted by 1D rad-hydro calculations. Yield degradation was predominantly found to occur in the compression component, with little effect on the shock yield. Increased fuel/shell mix as a result of ^{3}He addition does not provide a reasonable explanation. Instead, observations appear consistent with reduced compressibility, relative to calculations, of the capsule with ^{3}He addition. Several potential mechanisms are being explored to explain this reduced compressibility.

The paper is organized as follows: Previous work and motivations for the current study are presented in Sec. II, the experimental setup is presented in Sec. III, experimental observations are presented in Sec. IV, a discussion covering reduced compressibility and fuel/shell mixing is presented in Sec. V, and conclusions are presented in Sec. VI.

II. MOTIVATION FOR ^{3}He IN DT

The use of surrogate fuels provides a means of characterizing capsule performance without incurring the complications associated with the high fusion output of DT fuel. D_2 has been the most commonly used surrogate, but the primary interest is in DT since the first igniting capsules will surely contain pure DT. When an unexplained anomaly is discovered using a surrogate, it is not obvious whether this anomaly will also exist for DT and thus must be verified. The incorporation of ^{3}He appears to provide such an anomaly. Once understood, this anomaly could potentially lead to new physics insights and might even prompt the intentional addition of ^{3}He to DT as a diagnostic tool.

While the use of DT may complicate some diagnostic methods, it also enables the use of other valuable techniques. The high fusion output coupled with a relatively high fusion gamma-to-neutron branching ratio for the DT reaction enables the measurement of the 16.75 MeV gamma rays that are emitted in just a few of every 100 000 DT fusion reactions. The time-resolved GCD was used in these studies for measurement of quality reaction histories based on the DT gamma ray.

Previous ICF implosions have revealed the possible anomalous effect (i.e., beyond what is predicted) on fusion yield arising from mixtures of D_2 and ^{3}He. The most notable is a study led by a team of Massachusetts Institute of Technology (MIT) researchers in which a series of plastic capsules containing "hydroequivalent" mixtures of $D_2/^3$He was imploded at the OMEGA laser.[5] They discovered that the compression and shock yield components were degraded relative to predictions scaled from pure D_2, with the maximum deviation occurring at 50% ^{3}He by atom.

Hydrodynamic equivalency was satisfied in this previous study by maintaining a constant Atwood number. This is achievable since D and ^{3}He have the same value of $(1+Z)/A$, where Z is the atomic number and A the atomic mass. Mixtures can then be chosen such that the mass density and total particle density (ions+electrons) are identical. This is accomplished by exchanging three D atoms for two ^{3}He atoms. Once the fuel is fully dissociated and ionized after the first passage of the laser-driven shock, the fuel is predicted to behave as an ideal gas ($pV=nRT$). Assuming that the different fuel gas mixtures achieve the same temperature profiles upon ionization, the compression and degree of shell/fuel mix for these mixtures should be nearly identical and the fusion yield should closely follow a simple scaling based on the fuel composition ratios. However, the MIT group observed that the scaled DD neutron and $D/^3$He proton yields, normalized to pure D_2, were lower than predicted by a factor of ~ 2 in mixtures containing 50:50 $D/^3$He by atom. These trends were observed for both shock and compression yield components. Measurements of the areal density (ρR) suggested that gas mixtures experience less compression than purer D_2 or ^{3}He target fills do, in contradiction to the hydroequivalent design hypothesis. Less compression alone, however, was not sufficient to explain the magnitude of the yield discrepancy. In addition, no single physical mechanism has been identified to explain the observations, particularly the nonmonotonic dependence on ^{3}He fraction. Comparisons of the current effort to this study will be presented in Sec. V A.

A similar abnormal effect from ^{3}He has been identified in glass capsule implosions during the "Hi-Z" experimental campaign at OMEGA being conducted by Los Alamos National Laboratory.[6] These experiments were also designed to be hydroequivalent. In this previously reported study, properly hydroscaled burn histories without and with ^{3}He (20% by atom) agree well until the time that the rebounding shock strikes the incoming shell, after which there is a divergence with less scaled yield coming from the capsule containing ^{3}He. Since the majority of shock yield occurs during the earlier period, the MIT conclusion that shock yield is anomalously affected by ^{3}He fraction is not supported. Degradation of compression yield, however, appears to be consistent with that observed by the MIT group. Implosions devised to be hydrodynamically equivalent are all expected to exhibit the same radius versus time independent of ^{3}He fraction. Contrary to this expectation, differences in shell radius with and without ^{3}He were observed from gated x-ray images during Hi-Z experiments. Shell x-ray emission suddenly brightens when the rebounding shock strikes the incoming shell. At this time, the x-ray image radii for the case with and without ^{3}He are in agreement and are consistent with simulation. After this time, however, the case with ^{3}He diverges, resulting in an $\sim 25\%$ larger radius at bang time than the case without ^{3}He and from the simulations with and without ^{3}He.

III. EXPERIMENTAL SETUP

Spherical SiO_x shells were fabricated by General Atomics using the glow discharge plasma method. The capsules had a mean diameter of 1098 ± 5 μm and a 4.7 ± 0.05 μm average wall thickness. All capsules were filled with 5.1 atm of 50:50 DT gas at room temperature. Residual gases, pre-

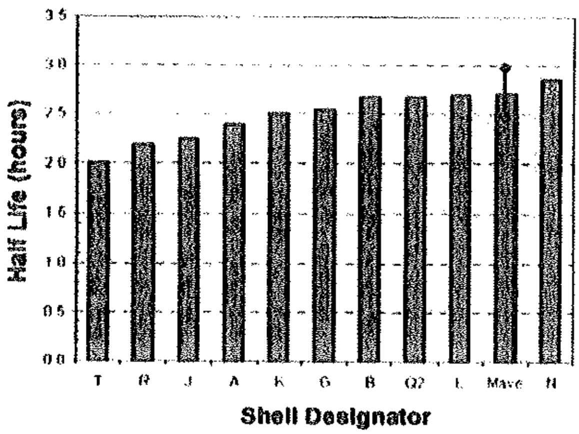

FIG. 1. (Color online) ^{3}He permeation half-lives for each individual SiO$_2$ shell used on shot day. Error bars on shell M show reproducibility of measurement

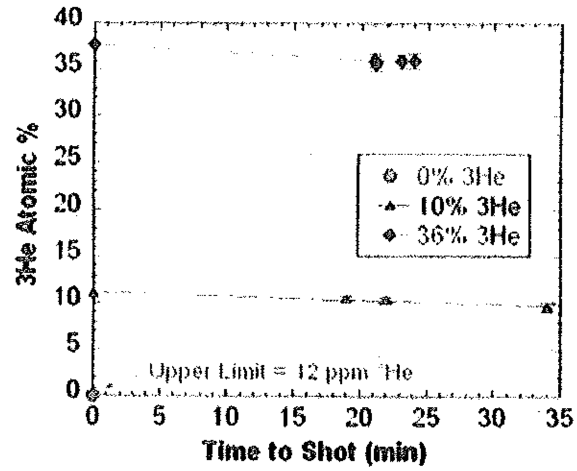

FIG. 2. (Color online) Estimated ^{3}He concentration at shot time based on individual leak rates of Fig. 1. Capsules contained ~5 atm of DT at shot time. Capsules were stored for several days in cells pressurized with ^{3}He to either 0, 1.26, or 6.05 atm, resulting in ^{3}He atomic concentrations at shot time averaging 0%, 10%, or 36%, respectively. Data points on the y axis represent the ^{3}He concentration just before depressurization of the gas cell and are for illustrative purposes only.

dominantly CO_2 and CO, were estimated to be <0.13 atm. ^{3}He was added after the DT fill, increasing the overall pressure. Three ^{3}He partial pressures were chosen, producing capsules that were not hydrodynamically equivalent to one another, and thus shot-to-calculation comparisons were required for analysis. Future experiments will strive to obtain hydroequivalency, making analysis of shot-to-shot comparisons more direct.

Accurate knowledge of the ^{3}He partial pressure in the capsule at shot time is critical for measuring ^{3}He effects on ICF implosions. Helium, being a small atom, naturally has a much higher permeation rate than hydrogenic molecules such as D_2, DT, and T_2. Typical room-temperature permeation half-lives for DT through thin glass shells are on the order of 10 weeks, whereas the half-life for ^{3}He is only a few hours. To minimize uncertainty, ^{3}He permeation rates for each individual capsule were measured by a pressure increase method[7] after the shells had already been filled with 5.1 atm of 50:50 DT gas. The results, shown in Fig. 1, indicate a mean ^{3}He permeation half-life of 2.5 h. All permeation rates were within ± 0.5 h of this mean. Capsules were stored in individual ^{3}He-pressurized containers to prevent leakage.

Shells were kept on dry ice to minimize leakage of DT. Exceptions to this include short periods at room temperature to: conduct the ^{3}He permeation tests; mount and place them in the ^{3}He-pressurized cells; and prepare them for target chamber insertion on shot day. Time at room temperature was carefully recorded to produce an accurate estimate of DT partial pressure at shot time. The time between taking a target from a ^{3}He-pressurized cell and shot time was also recorded. To minimize ^{3}He leakage and the uncertainty in the ^{3}He partial pressure at shot time, this delay was kept as short as practical. Figure 2 shows the estimated ^{3}He concentration as a function of the time to shot for the three separate fill pressures. The delay between taking a target out of a ^{3}He-pressurized cell and shot time was limited to less than 35 min for all shots, with all but one shot occurring within 25 min. As a result, uncertainty in the ^{3}He concentration was better than ±3%. It is estimated that the targets that were not intentionally filled with ^{3}He had no more than 12 ppm ^{3}He resulting from equilibrium between continuous source (tritium decay) and loss terms (permeation).

Direct-drive implosions of these targets were conducted at OMEGA using 60 beams of frequency-tripled (351 nm) UV light in a 0.6 ns square pulse and a total energy of 16.3 kJ with no smoothing by spectral dispersion. This relatively short laser pulse (as compared to the more typical 1 ns pulse used in the other previously cited studies) was chosen to reduce and delay the compression component of the yield so that the shock component would be more discernible in neutron and gamma-based reaction history measurements. As-shot conditions are summarized in Table I.

IV. EXPERIMENTAL OBSERVATIONS

The addition of ^{3}He decreases the neutron yield as shown in Fig. 3. The yield was measured by the neutron time-of-flight detector (nTOF) installed at 12.4 m from the target.[8] Shot-to-shot reproducibility was better than ±10% about the mean. DT fusion neutron yield drops by 80% between 0% and 36% ^{3}He by atom. Also plotted is the independently determined DT fusion gamma yield as measured by the GCD which shows the same trend in neutron yield as a function of ^{3}He concentration. A DT gamma-to-neutron branching ratio of 2×10^{-5} can be inferred from these data; however, uncertainty in the GCD absolute calibration is no better than a factor of 3 at this time. Recent values for the DT branching ratio vary from 5×10^{-5} to 1.2×10^{-4} gammas per neutron.[9-12] However, the measurements described in the literature are based on beam-target experiments with ion beam energies in excess of 100 keV and so may not be appropriate for thermonuclear fusion at ion temperatures ~5 keV. A 1D

TABLE I. As-shot conditions. Shell inner diameter and wall thickness refer to dimensions of the SiO_2 microballoon target. DT and ^{3}He pressures in the target at shot time are estimated from initial fill pressures corrected for DT and ^{3}He leakages based on time at room temperature and time outside of the ^{3}He-pressurized cell until shot time. Ion temperature (T_i) and neutron yield are determined using the nTOF instrument located at 12.4 m from the target chamber center. YOC is based on measured yields divided by predicted yields calculated assuming no fuel-shell mix (i.e., a clean calculation) in a 1D rad-hydro model.

Shot No.	Shell inner diameter (μm)	Shell wall thickness (μm)	DT pressure at shot time (atm)	^{3}He pressure at shot time (atm)	Total pressure at shot time (atm)	^{3}He fraction (at. %)	Laser energy (kJ)	nToF T_i (keV)	nToF n yield ($1\times10^{12}n$)	YOC
47875	1097	4.60	5.00	0.00	5.00	0.0	16	4.81	8.8	0.37
47877	1094	4.70	5.00	0.00	5.00	0.0	16.3	5.06	9.11	0.38
47881	1097	4.70	4.99	0.00	4.99	0.0	16.5	5.3	8.69	0.37
47879	1097	4.70	4.97	1.07	6.01	9.7	16.3	4.69	5.12	0.41
47873	1112	4.70	4.87	1.14	6.01	10.4	16.3	4.83	4.77	0.38
47876	1100	4.60	4.93	1.16	6.09	10.5	16	4.64	4.19	0.33
47880	1098	4.60	4.97	5.51	10.48	35.7	16.4	4.94	1.69	0.39
47874	1098	4.70	4.94	5.53	10.17	35.9	16.4	4.55	1.7	0.40
47878	1093	4.60	4.96	5.57	10.53	35.9	16.4	5.15	1.5	0.35
47882	1096	4.60	4.95	5.58	10.52	36.0	16.3	4.87	1.43	0.33
0% ^{3}He ave.	1096.0	4.67	5.00	0.00	5.00	0.0	16.27	5.06	8.87	0.37
10% ^{3}He ave.	1103.0	4.67	4.92	1.12	6.05	10.2	16.20	4.72	4.69	0.37
36% ^{3}He ave.	1096.3	4.63	4.95	5.55	10.50	35.9	16.38	4.88	1.58	0.37
Overall ave.	1098.2	4.65	4.96				16.3	4.9	4.7	0.37

radiation hydrodynamic simulation, assuming no mixing between the shell material and fuel during compression (i.e., clean calculation), shows that the measured yield is ~0.37 of calculated for all ^{3}He concentrations. This is reflected in the value of yield-over-clean (YOC) in Table I. This constant scale factor may be somewhat coincidental, however, as will be discussed in Sec. V.

Fusion reaction histories based on DT gammas measured using the GCD and DT neutrons measured using the neutron temporal diagnostic (NTD)[14] are shown in Fig. 4. Since the relative time base of the GCD instrument is not absolutely calibrated, it is cross calibrated against the absolutely calibrated NTD by matching bang times on what was considered to be the shot with the best quality NTD data (shot 47877). The time base offset relative to an optical timing fiducial is determined from this "best case." This offset was then applied to the GCD timing, also relative to the optical timing fiducial, for the remaining shots.[14] Postprocessing to remove instrument temporal response was performed on both reaction history diagnostics. The standard NTD algorithm[15] was used to remove the 1.2 ns decay time of the NTD scintillator and additional smoothing was applied. Deconvolution is able to remove much of the GCD instrument impulse response time of approximately 135 ps full width at half maximum (FWHM), leaving a residual response of approximately 70 ps FWHM. The GCD-based reaction histories for 0% ^{3}He show

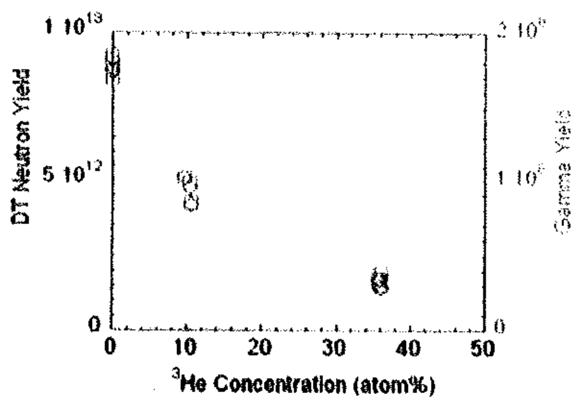

FIG. 3. (Color online) DT neutron and gamma yields as a function of ^{3}He concentration measured by nTOF (blue diamonds) and GCD (red squares), respectively. Typical absolute yield uncertainty for the nTOF is ~10%. Typical relative yield uncertainty for the GCD is also ~10%, but absolute yield uncertainty is greater due to uncertainties in GCD absolute calibration and the DT-γ/DT-n branching ratio.

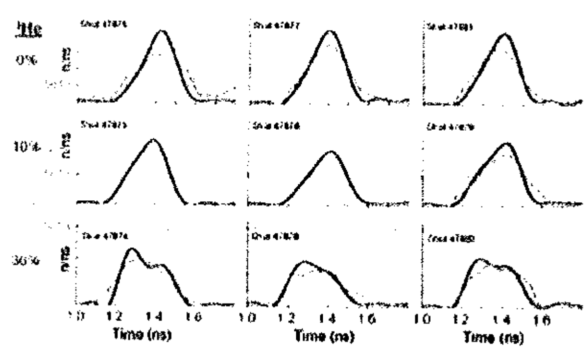

FIG. 4. (Color online) DT fusion reaction histories from the GCD (solid blue line) and the NTD (dashed pink line) show the growth of a feature near 1.25 ns as ^{3}He is added. Instrument response has been deconvolved from the data for both detectors. No NTD data were acquired on two shots (47873 and 47876). NTD data for shot 47877 were used to establish an absolute time base for the GCD data.

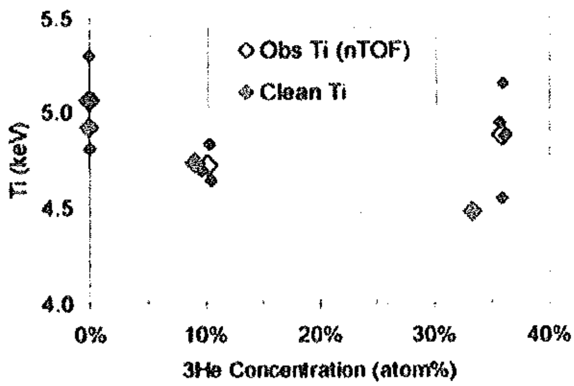

FIG. 5. (Color online) Burn averaged ion temperature measured by neutron time-of-flight (nTOF) in solid black diamonds (blue online), the mean of the measurements in open black diamonds (blue online), and a clean calculation (i.e., no shell/fuel mix) in solid gray diamonds (pink online).

an asymmetry which evolves into an observable feature on the leading edge of the GCD signal at 10% ^{3}He addition and finally becomes a discernibly separate peak at 36% ^{3}He. The NTD-based reaction histories show qualitative agreement, but due to the relatively high level of noise observed in the raw data, they were determined to be not as useful for quantitative purposes. As a result, the discussion of Sec. V relies solely on the GCD-based reaction histories.

Time-integrated ion temperature measurements using the nToF are displayed in Fig. 5. There does not appear to be a strong temperature dependence with ^{3}He concentration although calculations indicate a monotonic temperature decrease with increasing ^{3}He, whereas a slight increase was detected in going from 10% to 36% ^{3}He.

The shell radius trajectory for one shot at 36% ^{3}He addition as inferred from gated x-ray images measured using the gated x-ray imager (QXI) diagnostic[16] is shown in Fig. 6. X rays become observable once the shock wave rebounding from the center strikes the incoming shell, establishing a time reference for comparison with simulation. Also shown

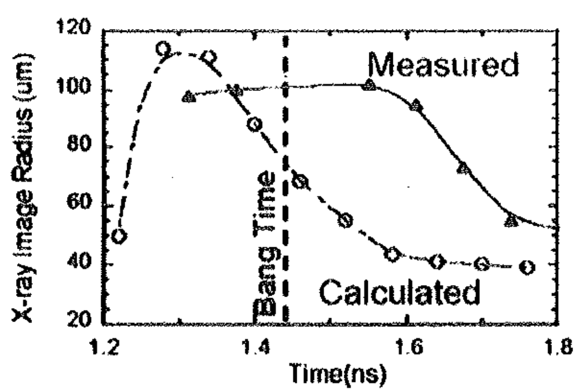

FIG. 6. (Color online) Temporal dependence of x-ray image radius for a 36% ^{3}He shot from the QXI (green diamonds) and clean calculation (open blue circles) shows less compression than expected.

are the simulated x-ray image radii based on the clean calculation. From the reaction histories, we find that the bang time for the compression component of yield occurs at about 1.44 ns. From Fig. 6 it appears that the shell radius is about 25% larger than simulated by a clean calculation at this bang time, corresponding to approximately a factor of 2 larger volume.

V. DISCUSSION

Several possible physical mechanisms pertaining to differences in composition, temperature, density, burn volume, and burn duration of the target during the implosion were explored in Ref. 5 in an attempt to explain the effect of mixtures containing ^{3}He. Some of them have the potential to explain reduced scaled yield in going from 0% ^{3}He to 50% ^{3}He, but none offers the possibility of explaining the recovery in scaled yield in going from 50% ^{3}He toward 100% ^{3}He. Although the current study has not yet explored the region from 50% to 100% ^{3}He, it is likely that this nonmonotonic behavior also exists in DT/^{3}He implosions and will be equally difficult to explain. Here we focus on the apparent symptoms of reduced compressibility and compression yield and their possible causes and then examine and attempt to discount fuel/shell mixing as a possible cause of the reduced compression yield by itself.

A. Reduced compressibility

Rather than simply investigate total yield degradation, it is more insightful to examine the shock and compression yield components individually as we explore mechanisms of yield degradation from the clean model. For this purpose, we decompose both the GCD-measured and the calculated reaction histories into two Gaussian components which are representative of the early shock yield and the later compression yield. The Gaussian decomposition for the GCD reaction histories are shown in Figs. 7(a)–7(c). These curves are a composite representing the three or four shots taken at each ^{3}He concentration. These composite GCD reaction histories are compared to the calculated reaction histories in Figs. 7(d)–7(f). It is evident that the observed compression yield degrades more quickly with increasing ^{3}He than is predicted by calculation.

The Gaussian fit parameters for the decomposed reaction histories of Fig. 7 are presented in Fig. 8. The observed (Obs) data points correspond to parameters derived from the GCD data, whereas the clean model results (Clean) are derived from the 1D rad-hydro code. In order to determine a goodness of fit for the Obs parameters, double Gaussians were convolved with the GCD instrument response function and adjusted to obtain the physically relevant optimal fit to the raw data. This allowed a sensitivity study to be conducted in which one parameter was varied while allowing the other five parameters to reoptimize the fit. It was found that the variation needed to increase the rms value of the fit by 5% was typically smaller than the shot-to-shot variation in the parameter (except when the shot-to-shot variation was exceptionally small). Thus, the parameters for the individual

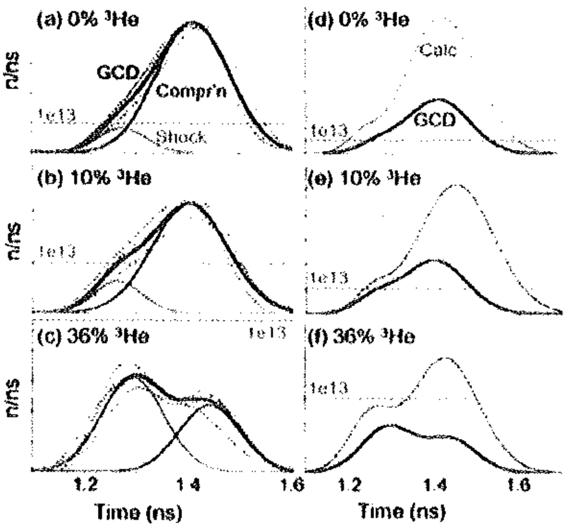

FIG. 7. (Color online) Gaussian decomposition of deconvolved reaction histories measured using the GCD instrument for (a) 0% ^{3}He, (b) 10% ^{3}He, and (c) 36% ^{3}He addition. Individual deconvolved reaction histories at each ^{3}He concentration are shown in dashed lines. Composites of the Gaussian fits to these reaction histories are shown in solid lines for the yield components arising from shock [gray (pink online)] and compression [black (blue online)], with their sum in bold black lines labeled GCD. Vertical scale is linear with the 1×10^{13} n/ns line shown in each case by a horizontal dashed line (red online) for reference. In (d)–(f) are shown the comparisons of the composites of the GCD measured reaction histories (black solid line) and calculated [dashed line (green online)]. Calculated histories are from a 1D rad-hydro "clean" calculation convolved with a 20 ps Gaussian to simulate instrument response.

shots are shown in $\times$'s and +'s for the Obs data set to give an indication of the amount of spread there is in data.

For the shock component of the yield, the clean calculation is reasonably consistent with the observations. These data are suggestive of a shock yield that burns at a slightly higher rate [Fig. 8(a)] for a longer period of time [Fig. 8(b)] than calculated. The resulting neutron yield [Fig. 8(d)] and bang time [Fig. 8(c)] for the shock component display reasonably good agreement between calculated and observed.

The compression yield, however, shows a considerable discrepancy between calculated and observed, with the calculated peak yield rate, FWHM, and resulting compression neutron yield being significantly higher than observed. The FWHM diverges significantly from the clean calculation as ^{3}He is increased, implying a shorter compression burn. Bang times are in reasonable agreement for compression components, as they were for the shock components.

The ratio of the observed yields to the clean calculated yields using the Gaussian fit parameters is shown in Fig. 9. The observed yield for shock is ~40% above the calculated yield on average. The shot-to-shot variation is large enough that there does not appear to be significant variation over the range of ^{3}He concentrations. The observed compression yield is 31% of calculated at 0% and 10% ^{3}He but drops to 17% of calculated yield at 36% ^{3}He. The total YOC ranges from 38% to 41% for the Gaussian fits, consistent with the ~37% YOC scaling determined Table I. The YOC remains relatively constant as the fixed shock yield makes up for the loss of compression yield with increasing ^{3}He, and thus appears to be somewhat coincidental.

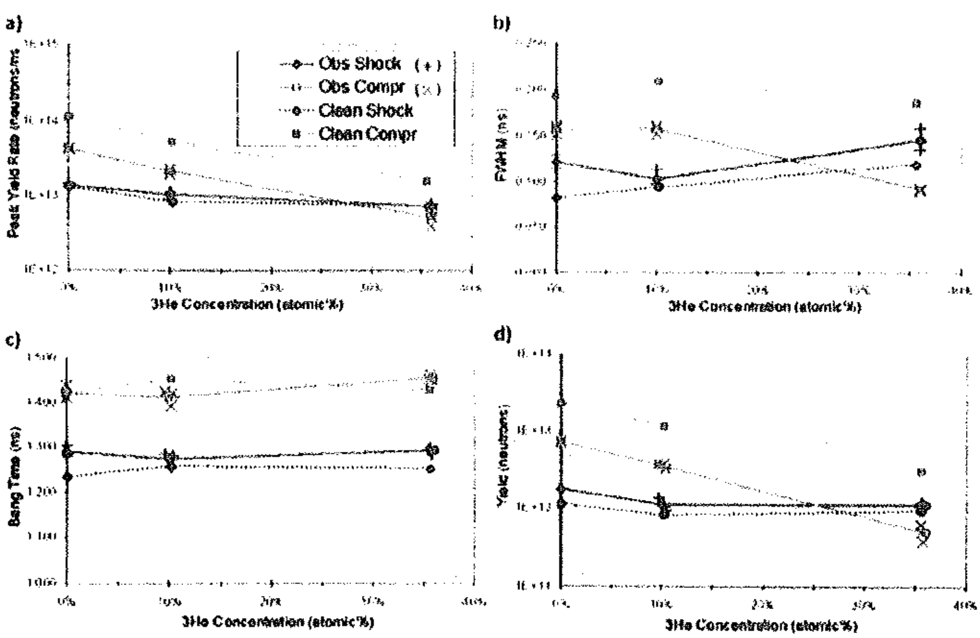

FIG. 8. (Color online) Reduction in Gaussian fits into (a) peak burn rate, (b) full width at half maximum (FWHM, semilog scale), (c) bang time, and (d) neutron yield=1.06 × peak burn rate × FWHM (semilog scale). Parameters from the forward-folded fit to experimentally measured reaction histories are shown in +'s and ×'s, with their averages in open symbols/solid lines (i.e., Obs) and those from the fit to calculated reaction histories assuming no mix are shown in solid symbols/dashed lines (i.e., Clean). Shock components are in black (blue online) and compression components are in gray (pink online).

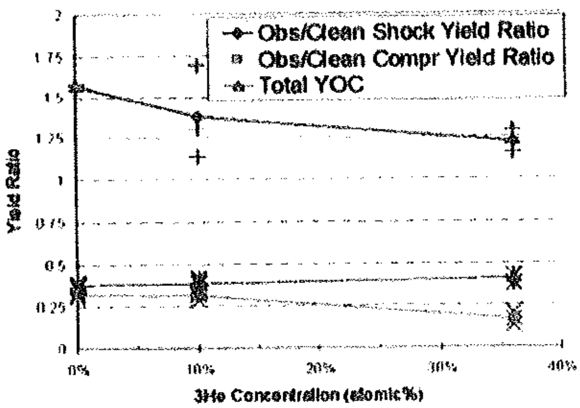

FIG. 9. (Color online) Ratio of observed to clean calculated yields from Fig. 8(d).

The observed YOC for the compression yield from Fig. 9 is replotted in Fig. 10(a) after normalizing the data to 1 at 0% ^{3}He so that a direct comparison to the MIT results can be made. It can be seen that the anomalous compression yield degradation in DT/^{3}He-filled glass capsules is consistent with that previously seen in D_2/^{3}He-filled plastic capsules.

The YOC for the shock yield from Fig. 9 is replotted in Fig. 10(b). For the shock yield we see reasonable agreement with calculation, whereas the MIT study observed a non-monotonic trend for the 24 μm thick capsules very similar to what was observed for compression yield. For the 20 μm thick capsules, however, there does not appear to be a strong trend with ^{3}He. It should be noted, however, that the 20 μm shock yield data were considered to have too high a level of uncertainty from which to draw any conclusions, hence the lack of error bars. As previously mentioned, a Los Alamos National Laboratory study using D_2/^{3}He-filled glass capsules also observed YOC trends that were consistent with the MIT compression yield results but did not see an anomalous effect in shock yield. It should be noted that yields from different nuclear reactions are being compared in Fig. 10. The Los Alamos National Laboratory (LANL) results are for DT-γ (previously shown to be proportional to DT-n in Fig. 3), while the MIT compression yield results are determined from DD-n and the MIT shock yield results are determined from D^{3}He-p. The expectation is that these various reactions adequately represent the shock and compression yield trends with ^{3}He addition and thus enable a valid comparison.

The gated x-ray imaging measurements shown in Fig. 6 are consistent with less compression than predicted for 36% ^{3}He addition. No useful x-ray imaging data were obtained for the other ^{3}He concentrations. A 25% larger outer shell radius corresponds to approximately a factor of 2 less fusion yield, assuming a fixed shell ρR and fuel ion temperature such that the fusion yield is roughly proportional to $n_D n_T V \sim 1/r^3$. Less compression is likely to result in lower ion temperature, reducing the yield further. However, it should be noted that without a similar analysis of x-ray images for 0% and 10% ^{3}He, these arguments are not conclusive.

The nToF measurements shown in Fig. 5 are also consistent with reduced compression at 36% ^{3}He. The nToF ion temperature is a burn averaged measurement. It becomes skewed to higher temperature when the shock yield component becomes comparable to compression yield, owing to the higher ion temperatures that occur during shock yield. The ratio of compression to shock yield at 36% ^{3}He is about 3:1 in the calculation and 1:2 in the experiment, as can be seen in Fig. 8(d). Assuming that the ion temperature is 6.5 keV during shock and 4 keV during compression, the burn averaged ion temperature for 36% ^{3}He should go from ~4.4 keV in the calculation to ~5.0 in the experiment, similar to the results of Fig. 5. Thus, the unpredicted increase in T_i in going from 10% to 36% ^{3}He can be explained by the unpredicted decrease in compression yield.

The underlying assumption of previous experiments examining the effect of ^{3}He is that the capsules are truly hydrodynamically equivalent. This is based on the knowledge that the ionized gas acts as an ideal gas. However, the details of the original nonionized molecular gas will determine the shock jump conditions and thus the initial conditions for the compression of the ideal gas. Additionally, the hydroequivalency is based solely upon charged particle number density and mass density equivalency but has a discrepancy in the

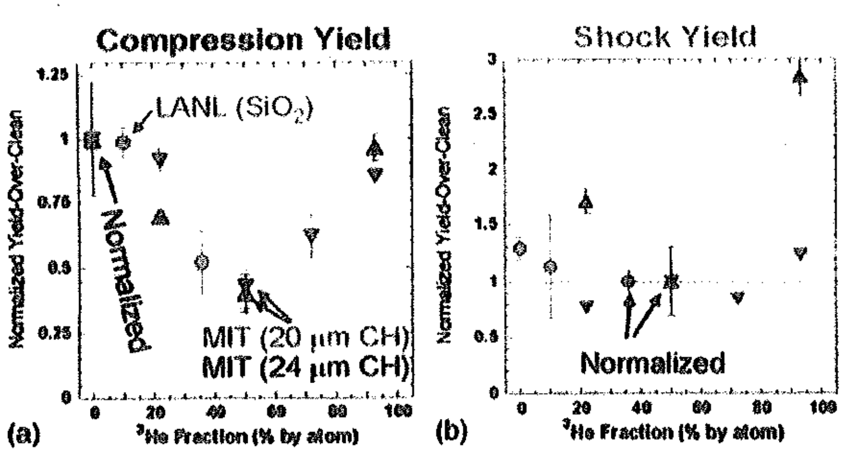

FIG. 10. (Color online) YOC for (a) compression yield component normalized at 0% ^{3}He and (b) shock yield component normalized at 50% ^{3}He for the MIT study and no normalization for the current study. In both frames, the MIT D_2/^{3}He-filled plastic capsules are shown in light blue downward pointing triangles for 20 μm thick CH capsules and dark blue upward pointing triangles for 24 μm thick CH capsules. The current study using DT/^{3}He-filled 4.7 μm thick glass capsules are shown as solid red circles. The LANL results are for DT-γ, while the MIT compression yield results in (a) are determined from DD-n and the MIT shock yield results in (b) are determined from D^{3}He-p.

individual ion and electron number densities since He contributes more electrons than D. This discrepancy leads to a change in the way energy is distributed between the ions and electrons in the fuel, and thus potentially causes a deviation from true hydroequivalency.

These arguments prompted exploration in a new direction. Perhaps differences in equation of state (EOS) between DT and mixtures containing ^{3}He may be responsible for the observed behavior. Typically, the radiation hydrodynamics codes use an EOS for deuterium and isotopically scale this EOS to tritium and ^{3}He. Cooley *et al.*[17] found that the use of a proper mixture of DT EOS and ^{3}He EOS has the effect of changing the initial conditions of the ionized fuel and as a result reducing the compressibility and compression yield with increased ^{3}He.

In addition, preheating of fuel is being questioned.[18] If ^{3}He is substantially more heated by fast electrons than DT, then a higher temperature and pressure may result in less compressibility. However, initial studies indicate that a significant amount of preheat would be required to achieve the factor of 2 reduction in scaled yield. In addition, this mechanism is unlikely to explain the nonmonotonic behavior.

B. Mix

As previously noted, the YOC for all three ^{3}He concentrations was ~0.37. An often-used method for degrading the clean yield is to apply fuel/shell mixing models.[19] It is unlikely that mix will result in less compressibility but must be examined as a possible cause of reduced compression yield since we have not conclusively demonstrated that the capsules do not compress as much as predicted at 36% ^{3}He.

Employing the Scannapieco and Cheng dynamic mix model,[20] it is found that a value of 0.065 for the mix parameter (α) is required to reduce the total yield to match the experiment with no ^{3}He. This value of α is in reasonable agreement with past experiments and fuel/shell mix may very well provide a reasonable means to explain the yield degradation at 0% ^{3}He. However, this same value of α does not explain the degradation when ^{3}He is added. It is found that a significantly larger alpha, or more mix, is needed for larger values of ^{3}He concentration. The value of α must increase to 0.09 at 10% ^{3}He and 0.15 at 36% ^{3}He. Since additional ^{3}He also means additional pressure in the capsule (more than double in going from 0% to 36% ^{3}He) and therefore increased resistance to hydrodynamic instabilities, it is expected that the required alpha would decrease with increasing ^{3}He, not increase. Such pressure stabilization has been observed previously.[19] In addition, mix is expected to produce an increasing degradation in burn rate as the mixed material propagates toward the core. This should modify the reaction history by truncating the burn is such a way that the bang time for the compression component occurs earlier and the FWHM is reduced. Although a significant reduction in compression FWHM is observed, the observed compression bang times shown in Fig. 7 agree well with calculation and are relatively independent of ^{3}He concentration.

Thus, it appears unlikely that increased fuel/shell mix with increasing ^{3}He is a viable explanation for the observed behavior.

VI. CONCLUSIONS

The anomalous degradation in measured yield previously observed in $D_2/^3$He-filled plastic and glass capsules has now been observed in DT/^{3}He-filled glass capsules in direct-drive ICF implosions. However, unlike the MIT results for $D_2/^3$He-filled plastic capsules, the anomaly appears to primarily affect the compression component of yield and not the shock component. These observations are consistent with the results of a previous Los Alamos National Laboratory study using $D_2/^3$He-filled glass capsules. The results are not consistent with increased fuel/shell mix with increasing ^{3}He. Diagnostic signatures are consistent with reduced capsule compressibility with increasing ^{3}He addition. These include lower compression yield as determined by reaction histories measured using the GCD and NTD, larger shell radius as measured by gated x-ray imaging, and larger ion temperature as measured by nToF. Several hypotheses have been advanced but not conclusively proven.

Two future experiments can provide additional information to test these hypotheses. First, hydrodynamically equivalent DT/^{3}He gas mixtures will allow better shot-to-shot comparisons with less reliance on shot-to-calculation comparison.[21] Second, ^{3}He fractions greater $\gtrsim$50% would investigate the nonmonotonic behavior previously observed in $D_2/^3$He implosions.

ACKNOWLEDGMENTS

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[21] Preliminary hydroequivalent DT/^{3}He capsule experiments appear to be consistent with reduced capsule compressibility. These experiments will be reported separately once more data are gathered.

NIC

Gamma-Ray Physics Efforts on NIF & OMEGA

LANL P-24 Seminar

Nov 30, 2010

H.W. Herrmann

Los Alamos National Laboratory

(on Change-of-Station to NIF)

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Y.H. Kim, N. Hoffman, A. McEvoy, D.C. Wilson, C.S. Young, J.M. Mack, J.R. Langenbrunner, S. Evans, T. Sedillo, S. Batha,...

Los Alamos Nat'l Lab

W. Stoeffl, L. Bernstein, P. Watts, A. Lee, J. Celeste, T. Thomas, G. Holtmeier, S. Poor, L. Dauffy, S. Azevedo, J. Liebman and the *NIF* Team

Lawrence Livermore Nat'l Lab

C.J. Horsfield, M. Rubery, W. Garbett

Atomic Weapons Establishment

E.K. Miller, R. Malone, M. Kaufman, B. Cox, Z. Ali, T. Tunnell,...

Nat'l Security Technologies

E. Grafil

CO School of Mines

V. Yu. Glebov, T. Duffy and the *OMEGA* Team

Laboratory for Laser Energetics

NIC

Outline

- Intro
  - Fusion Reaction History
  - γ-Ray Gas Cherenkov Detectors
- OMEGA Summary
  - Ablator areal density measurements
  - DT Fusion γ-Ray Spectrum & Branching Ratio
  - Anomalous DT yield degradation due to ^3He addition
- Gamma Reaction History Diagnostics (GRH) for NIF
  - GRH-6m for THD
  - GRH-15m for DT Ignition
- NIF γ-ray Measurements
  - Timing Calibrations
  - Reaction History (Bang Time & Burn Width)
- Future Directions
  - New Diagnostic Capabilities
  - Physics Studies
- Summary

Anomalies due to 3He addition to DT fuel (explored during LANL's DTRatio Campaign) might be explained by Peter Amendt's new Barodiffusion Theory

PHYSICS OF PLASMAS 16, 056312 (2009)

Anomalous yield reduction in direct-drive deuterium/tritium implosions due to ^{3}He addition[a)]

H. W. Herrmann,[1,b)] J. R. Langenbrunner,[1] J. M. Mack,[1] J. H. Cooley,[1] D. C. Wilson,[1] S. C. Evans,[1] T. J. Sedillo,[1] G. A. Kyrala,[1] S. E. Caldwell,[1] C. S. Young,[1] A. Nobile,[1] J. Wermer,[1] S. Paglieri,[1] A. M. McEvoy,[1] Y. Kim,[1] S. H. Batha,[1] C. J. Horsfield,[2] D. Drew,[2] W. Garbett,[2] M. Rubery,[2] V. Yu. Glebov,[3] S. Roberts,[3] and J. A. Frenje[4]
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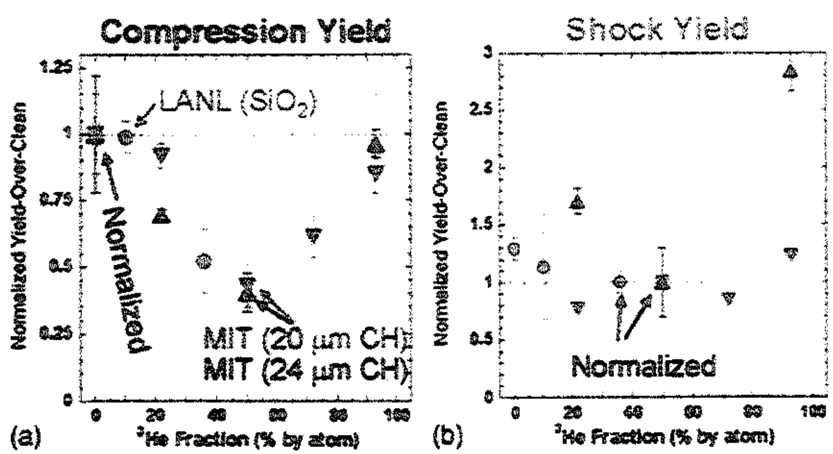

PRL 105, 115005 (2010) PHYSICAL REVIEW LETTERS week ending 10 SEPTEMBER 2010

Plasma Barodiffusion in Inertial-Confinement-Fusion Implosions: Application to Observed Yield Anomalies in Thermonuclear Fuel Mixtures

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The observation of large, self-generated electric fields (≥10^9 V/m) in imploding capsules using proton radiography has been reported [C. K. Li et al., Phys. Rev. Lett. 100, 225001 (2008)]. A model of pressure gradient-driven diffusion in a plasma with self-generated electric fields is developed and applied to reported neutron yield deficits for equimolar D^{3}He [J. R. Rygg et al., Phys. Plasmas 13, 052702 (2006)] and (DT)^{3}He [H. W. Herrmann et al., Phys. Plasmas 16, 056312 (2009)] fuel mixtures and Ar doped deuterium fuels [J. D. Lindl et al., Phys. Plasmas 11, 339 (2004)]. The observed anomalies are explained as a mild loss of deuterium nuclei near capsule center arising from shock-driven diffusion in the high-field limit.

- Shock-driven diffusion in the presence of large electric fields leads to ion species separation, leaving a hot spot rich in Hi-Z (e.g., 3He), poor in Lo-Z (e.g., D & T)
  - ➢ leads to reduced yield
  - ➢ may also explain reduced compressibility
- Should affect only Compression Yield; not Shock Yield
  - ➢ MIT results see effect on Shock Yield
  - ➢ LANL results do not

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Proposed experiment: XXX will determine _____

- **Purpose:**
- **Motivation:**
- **FY11 Goal:**
- **PI/Designer:**
- **Major Issues:**

Summary Shot Table	*Q1FY11*	*Q2FY11*	*Q3FY11*	*Q4FY11*
Total shots				

Experimental Configurations for [campaign]

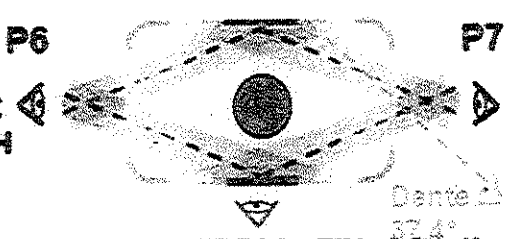
- ***This page should have a drawing (Visrad model if possible) of the experiment. Also a small summary of the laser beam requirements and diagnostics required should be included.***
- ***Example shown on slide 4 – can break into multiple slides if needed***

Targets

- **Include target drawing/sketch, dimensions and the "type" of target it is.**
- **Example on slide 5**
- *Type A: Developmental e.g. never been made before*
- *Type B: Complex e.g. produced before but has some schedule risk due to complex processes involved*
- *Type C: Routine/Simple e.g. hohlraums, witness plates, backlighter disks,…*

Example of experimental configuration

Experimental Config #1

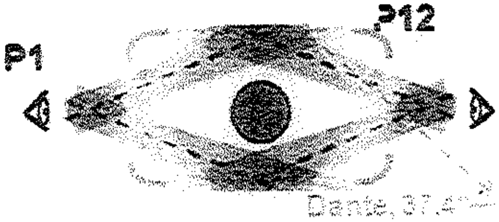


Laser config:

Beams	# CPPs	CPP size	Pulse	Special
20 (59°),	20	EIDI	1 ns sq	
10 (21°)	10	EIDI	1ns sq	
10 (42°)	10	EIDI	1ns sq	

Diag	TIM	Priority	Type	Calib/Chara
XRFC	5	1	3	Pre shot
XRFC	3	1	3	Pre shot
XRFC	4,6	2	3	Pre shot
DANTE		1	3	Pre shot
FABS		2	3	Pre shot
HXRD		2	3	Pre shot

Experimental Config #2



Laser config:

Beams	# CPPs	CPP size	Pulse	Special
20 (59°),	20	EIDI	1 ns sq	20 (59°), 10(21°)
10 (21°)	10	EIDI	1ns sq	10 (42)
10 (42°)	10	EIDI	1ns sq	

Diag	TIM	Priority	Type	Calib/Chara
XRFC	1	1	3	Pre shot
XRFC	3,5	1	3	Pre shot
DANTE		1	3	Pre shot
FABS		2	3	Pre shot
HXRD		2	3	Pre shot

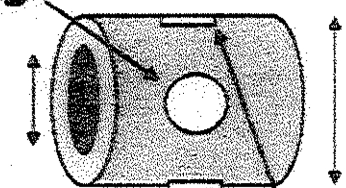
Example of Target Section

Target #1: Type A

Be capsule
1.4 mm OD

6.38 mm

1.9 mm



3.56 mm

Scale 0.7 1MJ 300 eV NIF
75% LEH
Au, standard wall

Patches
(thin Be or 0.5 µm polyimide)

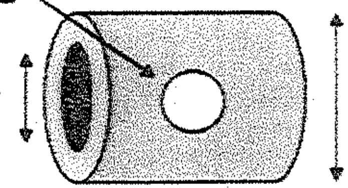
Target #2: Type B

The National Ignition Campaign

CH
1.4 mm OD

6.38 mm

1.90 mm



3.56 mm

Scale 0.7 1MJ 300 eV NIF
75% LEH
Au, standard wall , one patch